

DESCRIPTION OF OCCUPANT BEHAVIOUR IN BUILDING ENERGY SIMULATION: STATE-OF-ART AND CONCEPTS FOR IMPROVEMENTS

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ABSTRACT

Energy and indoor environmental performance of buildings are highly influenced by outdoor/indoor climate, by building characteristics, and by occupants' behaviour. Building simulation tools cannot precisely replicate the actual performance of buildings because the simulations are based on a number of basic assumptions that affect the results. Therefore, the calculated energy performance may differ significantly from the real energy consumption. One of the key reasons is the current inability to properly model occupant behaviour and to quantify the associated uncertainties in building performance predictions. By consequence, a better description of parameters related to occupant behaviour is highly required. In this paper, the state of art in occupant behaviour modelling within energy simulation tools is analysed and some concepts related to possible improvements of simulation tools are proposed towards more accurate energy consumption predictions.

INTRODUCTION

One of the most significant barriers for achieving the goal of improving energy efficiency of buildings is the lack of knowledge about the factors determining the real energy use. Often, there is a significant discrepancy between the designed and the real total energy use in buildings. The reasons of this gap are generally poorly understood and largely have more to do with the role of human behaviour than the building design. To investigate the influence of occupant behaviour on the energy performance of a building, many studies (Branco et al. 2004, Emery et al. 2006, Marchio et al., 1991, Nordford et al. 1994, Seligman et al. 1977-78, Sonderegger, 1977-78) focus the attention on the comparison of energy consumption of identical buildings, highlighting that the differences between real and predicted energy use depends on both the final realisation of the construction, the technical installations, and the real use of the built systems operated by occupants. Knowledge of such user actions is crucial to better understanding and more valid predictions of building performance (energy use, indoor climate) and effective operation of building systems (Hoes, 2009).

DESIGN AND PREDICTIVE TOOLS

The development process of software for building energy calculations (Clarke, 2001) started from a first (and second) generation, named "simplified methods", where the implemented mathematical formulations were very thin and characterized by many simplified assumptions (e.g. steady state calculation). The first developed software (first generation software) arose from the implementation of handbook type procedures, typically characterized by simplified schemes and operating in steady state condition, therefore providing only indicative results. Then, models were introduced that take partly into account the building dynamics for the energy performance evaluation (second generation software). Third generation software (the current generation of software) are associated with the name of "dynamic methods" (Hand, 1998), because thanks to development of computational technologies, they can model heat flows, electrical, lighting, sound simultaneously. Although these softwares present easier and more intuitive graphical interface and various functions have been introduced to help the process of data entry, they require modelling considerable experience for the user (Swan, 2009). Currently, a wide variety of simulation programs are available (ESP-r, TRNSYS, DOE-2, BLAST, Energy Plus, IDA ICE, Virtual Environment, etc.). Their complexity levels range from steady-state calculation to very sophisticated programs, including CFD simulation.

Assuming that the simulation is a theoretical representation of the status and operation of a building, it cannot perfectly replicate the real dynamics that govern the energy use: for example, the actual climate can vary from the meteorological data available, the systems may not work exactly as expected from the curves of load operation; performance may also vary with the age of the plant and the actual number of worked hours and the maintenance scheduled activity. Above all, the energy performance can be affected by the actual behaviour of the building occupants. Every building design is based on assumptions about how the building will be used, but when the building is realized, it may be used differently than its designer assumed or planned, affecting results validity.

Occupant behaviour may empathize between expectations and reality. For example, to face this topic, different assumptions to model the occupants' window-opening behaviour are made in literature: assumptions are the defined schedule window opening based on occupancy or the expectation that window opening to be controlled by temperatures, humidity, wind, rain or to produce an established airflow rate, supposing the occupants use the windows to achieve the design ventilation rates (Rijal et al., 2007). These assumptions do not necessarily represent the occupants' actual behaviour and for this reason, it is necessary to use algorithms for users interactions with the building control systems based on field investigations in real buildings. Actually, some algorithms have already been integrated in simulation software in order to explain with more accuracy some punctual aspects of the building energy use (e.g. Lightswitch models by Reinhart, 2004). Although a platform for the integration of occupant models (Bourgeois et al. 2006) into one software package exists, there is no complete and interlinked set of models considering all aspects of occupant behaviour.

Human behaviour and building simulation tools

From literature, it appears clear that models for human behaviour and for energy simulation are related to two different approaches (Boergson et al. 2008). Models of human behaviour are based on statistical algorithms that predict the probability of an action or event. For example, the existing empirical models of window operation tend to be based on statistical algorithms that predict the probability that an event occurs or has occurred (e.g. opening a window) at certain environmental conditions. They are based on observations of real windows in real buildings that allow statistical correlation between "window state" (open, partially open, closed, etc.) and outdoor temperature, time of day, season, indoor environmental conditions, etc. In other words, they consider window operation as a stochastic process where the probabilities of control events are based on environmental (indoor and outdoor) factors.

Building simulation tools, on the other hand, are based on heat transfer and thermodynamic equations, and typically model human actions (operation of lights, blinds and windows) basing on predefined fixed schedules or predefined rules (the window always open if the indoor temperature exceeds a certain limit). These tools often reproduce building dynamics using numerical approximations of equations modelling only deterministic (fully predictable and repeatable) behaviours. In such a way, "occupant behaviour simulation" could refer to a computer simulation generating "fixed occupant schedules", representing a fictional behaviour of a building occupant over the course of a single day (Goldstein et al, 2010). This is an important limitation of energy simulation tools for modelling

occupant's interactions with buildings, and highlights that the results are essentially unrealistic: lots of simulation codes for instance do not model the control of windows, but instead use its possible effect as input (through air change rate variation each hour). Moreover, buildings have multiple occupants, those occupants interact with one another and the behaviour of one occupant may differ from that of another. On this topic, J.A. Clarke (2006) proposed a probabilistic model of the discomfort and a second probabilistic model of actions taken in response to that discomfort to model stochastic occupant behaviour in buildings. Most building simulation tools integrate the effects of occupant presence within their calculations in a very simplified way, usually considering all occupants to be present according to a fixed schedule and multiplying the number of occupants by fixed values of metabolic heat gain. Other profiles, relating to small power or lighting gains, may also be entered on a similar basis. Occupants' interactions with window openings tend either to be defined by fixed schedules or by deterministic responses to physical stimuli. Window open behaviour has been shown to be poorly represented in commonly used building simulation tools (Dutton 2009): building energy simulation software, such as EnergyPlus and ESPr, combine the ventilation modelling of a network flow model with thermal energy simulation. As thermal effects influence the performance of natural ventilation systems, and ventilation performance impacts building energy performance, the combination can provide both more realistic building thermal performance and improved ventilation prediction. Published probabilistic models on occupant window behaviour, (Haldi et al., 2009 and Rijal et al., 2008), predict the probability of interaction with an individual window basing the on the assumption that the main driver of occupant window behaviour is discomfort. The basis of Rijal's model being that occupants only interact with their windows when they are thermally uncomfortable (defined as ± 2 °C either side of the adaptive comfort temperature). The "adaptive algorithm" (Humphreys & Nicol 1998) was implemented in ESP-r toward a more realistic thermal comfort and building performance assessment. These models, however, do not consider the state or quantity of adjacent windows in the room in their prediction of window state.

A widely used technique in energy simulation is to model the influence of occupants through diversity factors ("diversity profiles" for various categories of internal gains and types of buildings) to estimate the impact of internal heat gains (from people, office equipment and lighting) on energy and cooling load calculations (Abushakra et al. 2001). The profiles depend on the type of building (typical categories being "residential" and "commercial") and sometimes on the type of occupants (for example size and composition of a household).

ESP-r already offers some integrated behavioural models such as the Hunt model (Hunt 1979) for the switching of office lighting, the Lightswitch 2002 algorithm developed by Reinhart (2004) on the basis of Newsham et al.'s (1995) model to predict dynamic personal response and control of lights and blinds. Lightswitch is a sophisticated model for the interaction of occupants with blinds and lighting systems; using a simplified stochastic model of occupant arrival and departure. Bourgeois (2005) attempted to bridge the gap between energy simulation and empirically based information on occupant behaviour via a self-contained simulation module called SHOCC (Sub-Hourly Occupancy Control) to enable sub-hourly occupancy modelling and coupling of behavioural algorithms such as Lightswitch 2002 across many ESP-r domains. Page et al. (2008) hypothesized that the probability of occupancy at a given time step depends only on the state of occupancy at the previous time step. As suggested by Fritsch et al. (1990) in relation to window operation, Page et al. (2008) explored the use of Markov chains toward occupancy prediction. Page introduced a single influencing "factor"; specifically, the time of day. With this method, the simulation is calibrated using real schedules of presence and absence. If the real schedules tend to include a lunch break around noon, then the time of day factor allows that pattern of behaviour to be reproduced. Dealing with occupant activity simulation, in Tabak's User Simulation of Space Utilisation (USSU) System, there are many different tasks and occupants can interact via shared activities such as meetings and presentations. Unlike Page's method, USSU is not schedule calibrated, but questionnaire results are used to calibrate his model. In the recent years, the number of studies regarding occupants interactions with buildings' environmental control systems is increased, aiming at establishing a link between user control actions (or the state of user-controlled devices) and indoor or outdoor environmental parameter. On the other hand, even if most studies regarding occupant behaviour are conducted for individual building systems (lighting, shading, etc.), there are significant differences between the studies in terms of building size and type, relevant control devices (thermo-static radiator valves, shades, windows, etc.), duration of observation, measured environmental factors, and measurements' precision. However, these studies have provided a number of valuable insights into the circumstances and potential triggers of occupancy control actions in buildings. On the other hand, given the complexity of domain, additional long-term and (geographically and culturally) broader studies are necessary to arrive at more realistic models of control oriented user actions in buildings.

FROM DRIVERS TO ENERGY CONSUMPTION.

Human behaviour is the result of a continuous combination of several factors crossing different disciplines. The interactions operated by the occupant with the building control systems could be caused by a combination of both "external" and "internal" factors (Schweiker, et al. 2009). "External" factors are concerning the building science area (e.g. outdoor or indoor temperature), and they are being investigated by several researchers (Seligman et al. 1977-78, Nicol 2004, Schweiker et al., 2009, Haldi et al., 2009, Andersen et al. 2009). "Internal" factors are related to the social science area, in particular to the field of anthropology. The approach of this line of research is somewhat different from the approach used by researchers from the natural/technical science area. E.g., Hauge, 2012 conducted qualitative investigations in four European countries and showed that fresh air was a cross-cultural, social and emotional phenomenon. Interestingly, she arrived at some of the same conclusions as researchers coming from the field of natural/technical science: Herkel et al., 2008 (window opening most prevalent at arrival) and Toftum, 2009 (feeling of control improves comfort). Based on several studies, items referring to the occupant behaviour related to the building control can be defined and the general process leading to energy consumption can be identified as proposed in Figure 1.

Occupant behaviour influencing factors, both external and internal, defined here as "Drivers", are the reasons leading to a reaction in the building occupant and motivating him or her to operate an action (they "drive" the occupant to an action). These drivers include physical environmental, psychological, physiological, social and contextual factors. The central operator of this flux diagram is the *occupant* itself. Actually, with reference to indoor environmental quality, the occupant reacts consciously or unconsciously to an external or internal stimulus (drivers) to improve, sustain or restore the comfort conditions (Schweiker, 2009). "Action scenarios" are the occupant reactions to a driver or a combination of them: window opening or closing, set-point changes, clothing changes, etc. In general, behavioural actions cannot be regarded singular, because they continuously interact with each other and the borders cannot be distinguished in every case. The reactions could be determined both by "action logics" operated by both the occupants their self and the system control and partly the building behaviour itself. There are several possibilities for the occupants to control the indoor environment. First, they can operate directly aiming at controlling the indoor environment: the use of set-point and the ventilation system, the habits of opening or closing window and the habits of shading windows. Concurrently, occupants can make

operations having an effect on indoor environment indirectly, related to internal heat gains or energy use: appliances and equipment usage (TV, refrigerator, etc.), the quality of light, hot water, cooking. A third typology of users actions (affecting indirectly indoor environment) are represented by the adjustments of the occupants themselves to the existing environmental conditions. These operations include the change of place (the active movement within the room, the building or between building and outside), active body adaptation (change body posture or the amount of clothes worn), and the passive body adaptation (processes occurring within the human body in order to keep the core temperature stable within small limits). All the operations aimed by the occupants to improve or maintain the indoor environmental quality with respect to the previous perceived status have a consequence on the indoor environment. A variation in air change rates or room

air temperature are example of the “parameter variation” due to the window opening. Different action scenario outcomes could have a direct influence on both indoor environmental quality and the energy consumption. In figure 1, indoor environmental quality and energy consumption are the “process outputs”. The energy output could be minimal if actions scenarios are managed in a prudent way or maximum if the users follow actions logics scenarios maximizing the energy wasting. In this way, it is possible to identify different users’ behaviour typology depending on the way the actions sequences are performed. From an energy perspective, occupants could be named “energy saving users” or “energy wasting users”. From an indoor environmental perspective, occupants could be divided into “air quality users”, “thermal comfort users” or both.

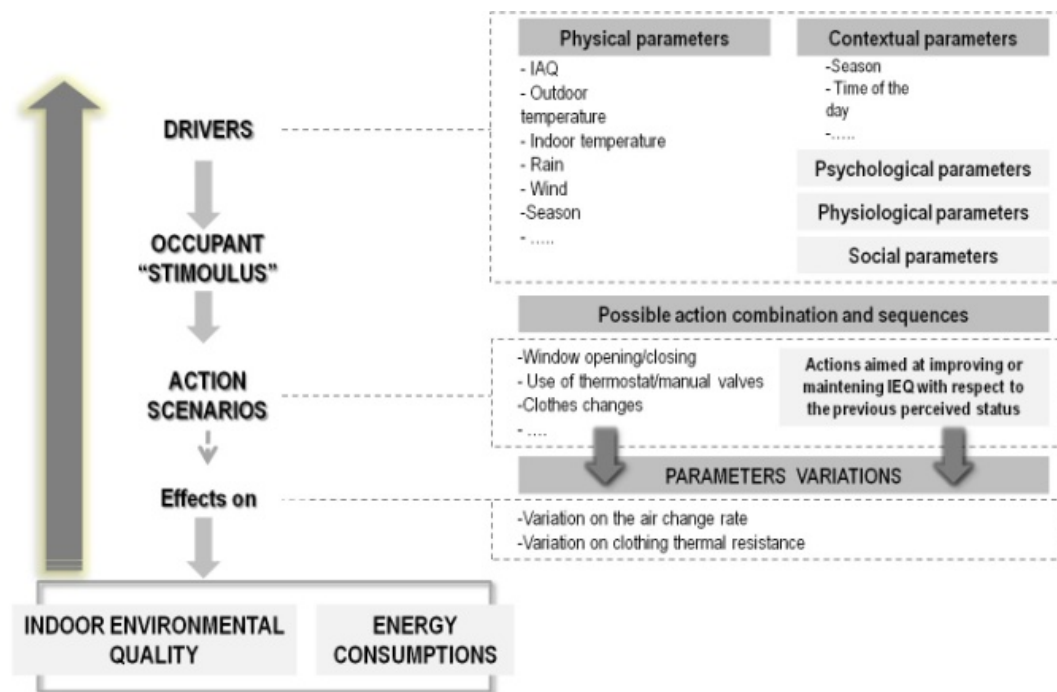


Figure 1 From drivers to energy consumption and indoor environmental quality

IMPROVEMENT AREAS OF EXISTING SIMULATION TOOLS

The focus of this section is to propose some possibilities to improve input and output parameters of building simulation tools, taking into account uncertainties.

The first area of investigation is related to a more accurate description of input parameters, starting from a better description of external climate up to occupant behaviours and building equipment operation and maintenance. Further improvements could be achieved by a deeper definition of the control strategies of the building technical systems

and actions by occupants (action scenarios) aimed at improving or maintaining the indoor environmental quality with minimum energy consumption. Detailed models and dynamic conditions are necessary to evaluate the building energy performance taking into account the parameters affected by human behaviour and the effects on the IEQ. A further level of improvement concerns the description of output data, in order to include new and clearer indexes for a synthetic description of the indoor environment and energy performance. This area of analysis should be concerned with the relationship between benefits of improving indoor environmental quality, corresponding energy consumptions or costs and

environmental impacts produced to obtain these benefits.

Improvement of the input parameters.

An accurate characterization of occupant actions is necessary to assess the efficiency of strategies aimed at reducing building energy consumption (such as day-lighting) and at the same time to ensure, or better, to improve, occupant comfort. The demand of realistic description of the real use of the building to better predict its actual energy performance becomes more and more evident after the improvements in building performance. Actually, input data in current simulation tools “hide” behaviours or preferences of the occupants and users, the schedule for air temperature for example covers the users’ preferences in terms of indoor temperatures. Improvements should concern specifically uncertainty and inaccuracy on input parameters. External climate, human behaviour, etc. are parameters permeated by randomness but these are often simulated in a deterministic way. The input parameters could be characterized by a probability density function (PDF): the input data, used to assess building energy performance, are always affected by uncertainties coming from different sources. These uncertainties will propagate via the model equations resulting in an uncertainty of the output. Therefore, the possibility to obtain accurate results mainly depends on the data quality. By uncertainty analysis (UA) it is possible to define an expected distribution of possible values for an outcome. The assessment of uncertainty gives information on how reliable the results are. Regarding the human behaviour (Figure

2), the goal should be to add to existing calculation tools dedicated “modules”. In current building energy simulation tools, the user behaviour is simulated in a static/restricted way (“deterministic”, fully predictable and repeatable). General assumptions are applied to describe user presence and action in a building or a room. The major flaw of these methods is the use of one or few profiles as the only and common behaviour of all the occupants in a building. Instead, modelling a parameter through its PDF may be used to define a “quality of an input parameter”. For example, the coefficient of variation of input parameters indicates a high or low degree of variability in relation to the mean value: a small coefficient indicates high quality. New description of input parameters should therefore be proposed, based both on PDF and on the outlines of occupant behaviour monitoring and on statistically based results. Moreover, the uncertainty of parameters which depend on occupants’ behaviour, such as ventilation rate, indoor set point temperature, internal heat sources and time patterns and on climate data could be reduced by on-field measurements. In this way, monitoring campaigns results should be integrated to have more accuracy of the parameters that will be input of a better prediction of energy consumption and indoor environmental quality. Obviously, the input parameters should be described in a different way according to the different design stages (from the concept to the final solution). The nature and the number of data used for building energy simulation should depend mainly on the analysis purpose and the thermal model used.

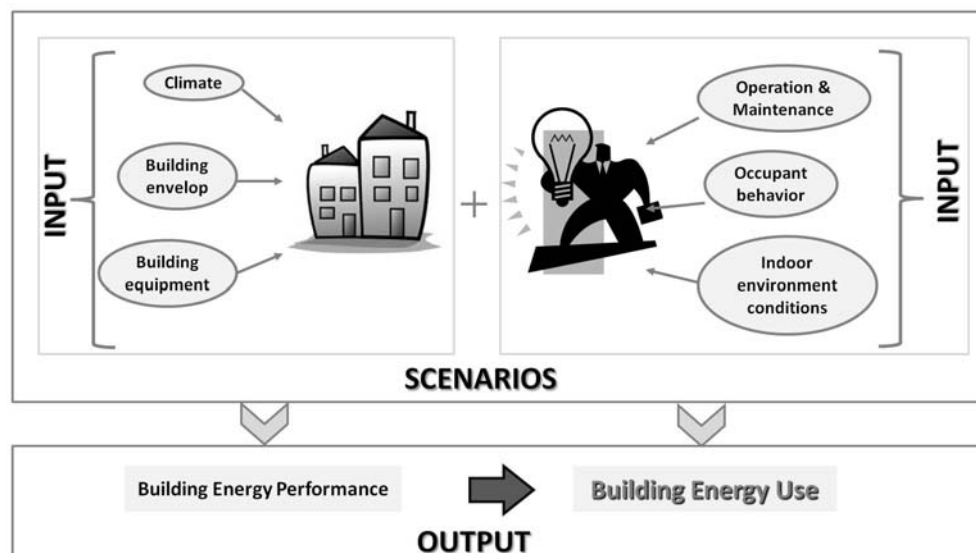


Figure 2 Area of interest of tools improvements, inspired by Annex 53.

Improvement of control and action logics.

Improvements of simulation tools could be achieved in the field of control and action logics. Controls

regard HVAC systems and in general, equipment, actions regards occupant behaviour. Calculation tools should be used to set up different control and action scenarios, developed in order to maintain the

required indoor environmental quality levels with minimum energy consumption at different design stages of the building. Moreover, the simulation tool improvements should regard the implementation of sensitivity analysis models to characterize the uncertainties in the output to evaluate the factors (combinations) that have the most important influence on the results and the interactions between these factors. In this way, it is possible to research priorities to reduce uncertainty on factors that are responsible for most of the variability in the output and to reduce uncertainty. This will consequently provide more confidence on the results. Moreover, by monitoring data it is possible to develop simple inverse models (by black or gray box approach) that fit the model response with respect to control scenarios for implementation in the detailed forward model. Again, monitoring campaigns could be useful to increase the level of description accuracy. These control and action logics should concern both the users and the building systems. In Figure 3, these tips of improving calculation tools are proposed. Calculation tools could be set up to give the possible combinations (scenario) to obtain the desired indoor environmental quality with the minimum energy consumption.

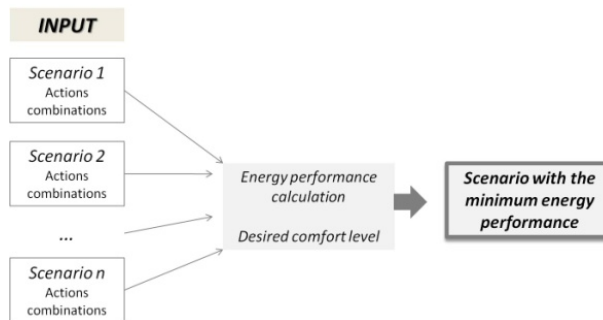


Figure 3. Integrate the actions logics into the simulation software

Improvement of output indicators.

Improvements of calculation tools should regard the description of the outputs as well. Existing dynamic simulation software is currently not yet able to clearly show the relationship between the calculated building energy performance and the indoor environmental quality level. This is because building performance indices are typically defined with reference to imposed and standard indoor environmental comfort conditions. In practice, there is a need to show the building energy class and the building indoor environmental class at the same time. This fact is fundamental to compare the performance of different buildings or to analyse different saving options in one specific building. Developments should be achieved on the integration of synthetic indices able to describe immediately the building performance not only in terms of energy consumption but also in terms of indoor

environmental quality performance. An important topic for the development of calculation tools is the benefits related to the improvements of indoor environmental quality. New tools should be able to give an overview of the relation between indoor environmental quality benefits and the energy demand including all the building life cycle. In particular, it should be investigated how to relate these two separated aspects: related-energy building demand and indoor environmental quality benefits. The major challenge is to define and propose a synthetic index expressing, at the same time, energy demand, for example defined by Euros, and comfort levels, defined by a suitable performance index.

CONCLUSIONS

The approach of building simulation is to create a virtual building where the user can specify in detail parameters that influence the building performance, with resulting performance predictions that are as close to reality as possible.

In this paper, starting from a survey aimed at highlighting the state of art in occupant behaviour modelling within energy simulation tools, some concepts and investigation procedures are proposed to improve the description of factors related to occupant behaviour and their influence on energy consumptions in buildings.

As building energy simulation tools have the capability to evaluate individual building design or retrofits, energy demands and performance, heating and cooling design, alternative technologies (energy efficiency and renewable energy), human comfort, capital and operating cost and atmospheric emissions a better description of the input parameters is necessary both in the design stage and in the performance prediction. Because of the lag in descriptions of input parameters, and because current software tools are based on deterministic approaches, they are not capable of realistic predictions of energy consumption and the related environmental quality. Simulation tools are often used to assess a buildings energy performance compared to the indoor environmental quality. In this way, it would be useful if the indoor environmental quality could be expressed in one synthetic index, including within the results some building and environmental quality synthetic performance indicators in order to explain briefly the achieved performance. Moreover, software packages are not nowadays capable of adequate evaluation of scenarios explaining the influence of occupant behaviour, but this is a crucial point in the efforts to minimize energy consumption.

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